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# EFFECT OF THE CONTENT OF CORN STALK FIBRES AND ADDITIONAL HEAT TREATMENT ON PROPERTIES OF ECO-FRIENDLY FIBREBOARDS BONDED WITH LIGNOSULPHONATE

*This study aims to find the possibility of producing eco-friendly thin Medium Density Fibrepanels (MDF) with the participation of corn stalk fibres and using lignosulphonate as a bio-based binder. The main novelty in the research is the establishment of the effect of additional heat treatment on the properties of MDF manufactured with the participation of non-wood lignocellulosic raw materials and bonded with bio-based adhesive – lignosulphonate. Panels with 15% lignosulphonate content and variation of the content of corn stalk fibres from 0% to 30% were manufactured. Previous experiments showed that when only lignosulfonate is used as a binder, the manufactured panels generally have low waterproofness. To reduce the effect of this main disadvantage, the panels were subjected additionally to heat treatment. The properties of the MDF with and without additional heat treatment were compared. The effect of both the content of corn stalk fibres and the additional heat treatment was found. As a whole, the additional heat treatment improves the properties of MDF produced with lignosulphonate. Still, in case of increased content of corn stalk fibres, it is necessary to apply softened regimes than the ones selected for this study.*

**Keywords:** dry-process fibreboards, eco-friendly, corn stalk fibres, lignosulphonate, additional heat treatment

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## Introduction

Forest territories worldwide are diminishing at the expense of the increasingly rising use of wood raw material for various productions, including the manufacture of wood-based panels and, in particular, of Medium Density Fibrepanels (MDF) [FAO]. That necessitates searching for alternative lignocellulosic raw materials [Abou-State et al. 1973; Chad and Fahim 2008; Savov et al. 2018; Grigorov et al. 2020]. Such ones may be wood-based panels for recycling, wood-based materials for recycling, etc. [Mantanis et al. 2004; Antov and Savov 2019; Iždinský 2020; Hagel and Saake 2020; Sala and Kowaluc 2020]. Most of the non-wood lignocellulosic raw materials are directed for the manufacture of biofuels [Limayem and Ricke 2012; Abdellatif et al. 2013; Arenas-Cárdenas et al. 2017; Fatma et al. 2018, Lim et al. 2012; Li et al. 2015], but their potential as a raw material in the manufacture of wood-based panels also remains considerable [Akgül et al. 2017; Bekhta. et al. 2018; Halvarsson et al 2009; Ihnát et al. 2015]. The main disadvantage of these raw materials is the increased hemicellulose content in them at the expense of the decreased range of cellulose and lignin [Lee et al. 2020; Moet al 2003]. Another characteristic of this raw material is the content of elements such as wax, silicon, pectin and ash [Kozlowski et al. 2004; Mirski et al. 2021; Rahman et al. 2018]. All this limits the content of this type of raw material in the panels and necessitates their preliminary treatment [Ramos et al. 2018; Zhang 2019; Zhang et al. 2000]. Corn is a widespread agricultural crop [FAO; Agrostat], with the corn stalks being a typical representative of lignocellulosic agricultural rests [Savov and Ivanova 2016; Theng et al. 2017; Ferreira et al. 2020].

The manufacture of eco-friendly materials and, in particular, panels leads to a striving for partial or complete replacement of formaldehyde-based binders with bio-based ones [Ferdosian et al. 2016; Diop et al. 2017; Hemmilä et al. 2017; Ghahri et al. 2018; Antov et al. 2021]. Lignosulphonates are a typical representative of this type of binder. Their main advantage in comparison with the other kinds of lignins is that they are water-soluble, which assists their introduction and uniform distribution in the wood-fibre mass [Gopalakrishnan et al. 2010; Savov,  and Mihajlova 2017 a; Savov and Mihajlova 2017 b; Hemmila et al. 2020; Antov et al. 2020 a; Antov et al. 2020 b]. The main disadvantage of lignosulphonates is that to form bonds with the wood fibres, stable in a humid environment, and it is necessary to apply a more considerable amount of energy, i.e. increased temperature and time of hot pressing [Savov et al. 2020; Antov et al. 2019; Savov and Antov 2020; Pizzi et al. 2020; Dunky 2020].

The additional heat treatment in the case of MDF leads to improved hydrophobic properties and deterioration of the strength and the modulus of elasticity in bending. It shall be underlined that the decrease of the strength properties of the panels after additional heat treatment is due to the changes in UF (urea-formaldehyde) resin, which took place [Winandy et al. 2007; Mohebby et al. 2008; Oliveira et al. 2017]. In the manufacture of MDF with lignin binders and, in particular, with lignosulphonates, the additional heat treatment improves the properties of the panels [Savov et al. 2020b]. This process is characteristic and still applied in many plants to manufacture wet-process fibreboards. A small amount of PF (phenol-formaldehyde) resin is used, especially if the panels are manufactured with biological materials binders [Back 1987; EPA, Widsten et al. 2009].

This research aims to study the effect of the content of corn stalk fibres on the properties of eco-friendly MDF and to find the impact of the additional heat treatment on the properties of these panels.

## Materials and methods

The supplied corn stalks were cut in slices 200 mm long and were immersed in water for 48 h. The immersion aims to separate, at least partially, the inorganic inclusions from the stalks and to increase their water content.

After this period, the corn slices were subjected to boiling, in mild mode – at a pressure of 1.05 atm (≈ 101 ºC) for 60 min. The pieces thus boiled were defibrated in a cylindrical laboratory mill "Defibrator". The pulp was dried in a drying cabinet at a temperature of 103±2 ºC, and the drying lasted for six hours. After that, the determining water content in the corn stalk mass was 10%.

Wood-fibre mass was industrially manufactured after the Asplund method, provided by WELDE BULGARIA AD. The pulp comprises the following tree species: beech – 57%, oak – 35%, poplar – 8%. The fibres were dried to 10% moisture content. The calcium lignosulphonate used for a binder has following properties: calcium – up to 6%; reduced sugars – 7%; ash content – 14%; dry content – 93%; acid factor in 10% solution – pH = 4.3 ± 0.8; bulk density – 550 $kg/m^3$. The lignosulfonate was introduced in pulp as a solution with a concentration of 40%.

Previous studies using lignosulphonates as a binder show that to produce quality panels, their content shall be on the order of 14-15% [Savov and Mihajlova 2017a; Savov and Mihajlova 2017b; Savov et al. 2019]. The content of calcium lignosulphonate in this study is 15%.

At present, thin and ultrathin composite materials are used in interior design and furniture production [Jivkov and Elenska-Valchanova 2019]. The thin panels have slightly increased density compared to MDF with a thickness of and above 16 mm [Jivkov and Petrova 2020). This type of panel is most often heavy MDFs or HDFs. In the present investigation, the manufactured eco-friendly panels have a set thickness of 6 mm and a density of 850 $kg/m^3$.

In previous studies, it has been found that in case of absence of chemical treatment of the non-wood lignocellulosic raw materials, including the corn stalks, their content in the wood-based panels shall not be above 30-40% [Ihnát et al. 2015; Bekhta et al. 2018; Lee et al. 2020]. That is why, in the present investigation, the content of corn stalk fibres is 0%, 10%, 20% and 30%. The panels manufactured entirely from wood raw material are control ones to find the effect of the inclusion of corn stalk fibres, Table 1.

**Table 1. Manufacturing parameters of the laboratory eco-friendly MDF panels produced from industrial wood fibres and corn fibres**

| MDF Type | Content of corn fibres *P*, % | Additional heat treatment |
|---|---|---|
| Type A | 0 | No |
| Type B | 0 | Yes |
| Type C | 10 | No |
| Type D | 10 | Yes |
| Type E | 20 | No |
| Type F | 20 | Yes |
| Type G | 30 | No |
| Type H | 30 | Yes |

The introduction of the binder was carried out using a high-speed (850 $min^{-1}$) laboratory blender with needle-shaped blades. The lignosulfonate was injected through a nozzle with a diameter of 1.5 mm, at a pressure of 0.4 MPa.

The hot-pressing was performed on a single-opening laboratory press type PMS ST 100, Italy. The process of MDF hot-pressing was as follows: In the first period, the pressure is increased for 20 s to 3.0 MPa and is maintained for 20% of the whole cycle, after which the pressure is uniformly reduced for 10 s to 1.2 MPa and is kept for 30% of the entire process, The last pressing period takes place at a pressure of 0.6 MPa for 50% of the whole cycle. The temperature of the press platens is 200 °C, at a press factor of 90 s/mm. The last parameters – temperature and press factor, were selected in conformity with previous investigations that show that for the manufacture of quality MDF with lignosulphonate as an independent binder, temperatures above 190 °C [Savov et al. 2020a] and a significant press factor [Savov et al. 2019; Savov and Antov 2020] shall be used.

Out of each composition of panels, two types each were manufactured – with and without additional heat treatment. Although the change in the hemicellulose structure starts from about 150-160 °C, the significant intensification of the process is at temperatures of 190-200 °C [Esteves and Pereira 2009; Altgen et al. 2016]. Of course, the intensity of the change in the wood structures is a direct function of both the treatment temperature and the treatment duration [Altgen et al. 2016; Gu et al. 2019]. In the present study, the additional heat treatment was performed in an oven with constant air circulation at a temperature of 170 °C and 40 min.

Eight test samples from each panel were used to determine the main properties of the panels (density, water absorption, thickness swelling, bending strength – MOR and modulus of elasticity). The tests were done by EN 310 – density; EN 317 – modulus of elasticity and bending strength; EN 323 – thickness swelling. A Zwick / Roell Z010, Ulm, Germany, universal testing machine was used to determine the mechanical properties of the panels.

## Results and discussion

The density of the manufactured panels was varied from 793 to 850 kg/m$^3$, i.e. this a relative change of 7%, Table 2.

**Table 2. Density of the laboratory eco-friendly MDF panels**

| MDF Type | Average (Mean) value, kg/m$^3$ | Standard deviation, kg/m$^3$ | Standard error, kg/m$^3$ | Probability, % | Confidence interval, kg/m$^3$ |
|---|---|---|---|---|---|
| Type A | 847 | 20.46 | 7.23 | 0.85 | 840÷854 |
| Type B | 845 | 12.98 | 4.59 | 0.54 | 841÷849 |
| Type C | 845 | 15.97 | 5.65 | 0.67 | 839÷851 |
| Type D | 847 | 39.62 | 14.01 | 1.65 | 833÷861 |
| Type E | 850 | 14.84 | 5.25 | 0.62 | 845÷855 |
| Type F | 805 | 39.64 | 14.01 | 1.74 | 791÷819 |
| Type G | 845 | 19.41 | 6.86 | 0.82 | 838÷852 |
| Type H | 793 | 24.15 | 8.54 | 1.08 | 785÷801 |

A considerable decrease in the density is noted in the panels with a content of corn stalk fibres of 20% and 30%, which are subjected to additional heat treatment. It shall be underlined that, in these panels, visible processes of destruction are observed.

The change in MDF density from first to seventh (MDF Type A to G) is from 845 to 850 kg/m$^3$, i.e. the relative change is 0.05%, which is considerably below the permissible 5%. That is confirmed by the conducted t-tests, which found that the only statistical difference in density values is between MDF Type E and F (*p*-value is 0.0139) and between MDF Type G and H (*p*-value is 0.0002). Therefore, it may be supposed that the recorded change in the density of the last panels is probably due to the destruction of the lignocellulosic components. The more significant hemicellulose content may explain this phenomenon in the corn stalks compared to the wood. As a result of which and due to the lower resistance of the hemicellulose in the panels with the content of corn stalk fibres, destruction processes take place to a greater extent.

The data for water absorption of the MDF panels are presented in Table 3.

**Table 3. Water absorption of the laboratory eco-friendly MDF panels**

| MDF Type | Average (Mean) value, % | Standard deviation, % | Standard error, % | Probability, % | Confidence interval, % |
|---|---|---|---|---|---|
| Type A | 57.78 | 6.57 | 2.32 | 4.02 | 55.50÷60.06 |
| Type B | 52.11 | 5.88 | 2.08 | 3.99 | 50.07÷54.15 |
| Type C | 69.91 | 5.60 | 1.98 | 2.83 | 67.97÷71.85 |
| Type D | 67.28 | 8.88 | 3.14 | 4.67 | 64.20÷70.36 |
| Type E | 80.32 | 8.71 | 3.08 | 3.83 | 77.30÷83.34 |
| Type F | 46.39 | 4.48 | 1.58 | 3.41 | 44.84÷47.94 |
| Type G | 88.55 | 8.97 | 3.17 | 3.58 | 85.44÷91.66 |
| Type H | 43.47 | 4.26 | 1.5 | 3.46 | 41.99÷44.95 |

The results for the water absorption of the panels in graphic form are presented in Fig. 1.

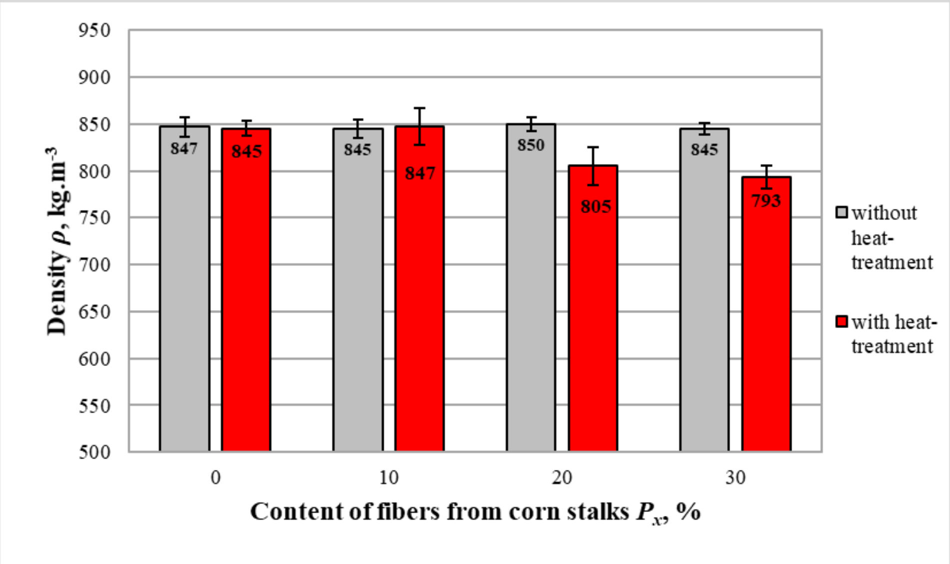


**Fig. 1. Density of eco-friendly panels (error bars represent standard deviation)**

The water absorption of the eco-friendly panels varies from 88.55% to 43.47%.

In the panels without the application of additional heat treatment, the trend for deterioration of the values of the property with an increase of the content of corn stalk fibres is distinct. The property is 1.53 times higher on the board, with 30% corn stalk fibres than wood manufactured. The deterioration of the property in case of the addition of corn stalk fibres is relatively uniform, i.e. no percentage inclusion, after which a sharp increase of this property takes place, is observed. Thus, in the case of the addition of 10% of corn stalk fibres, an increase of the water absorption by 12% (i.e. by 1.09 times) is observed in case of a rise in the content of corn stalk fibres from 10% to 20%, the increase of the property is by 11% (i.e. an increase by 1.14 times). In case of a rise in the content from 20% to 30%, the deterioration is 8% (i.e. 1.1 times). The performed t-tests show a statistical difference between the water absorption values between the panels with different content of corn stalks fibres. Thus, the *p*-value after t-tests between the water absorption values of MDF Type A and C is 0.0014, between MDF Type C and E is 0.0148, and between MDF Type E and G is 0.0181. That leads to the conclusion that increased content of corn stalk fibres worsens the water absorption of the panels, which was also proved by previous studies [Lee et al. 2020].

With the application of additional heat treatment, an improvement in the water absorption of the panels is observed. At 0% and 10% content of corn stalk fibres, the improvement is respectively by 1.11 times and 1.04 times. However, conducted t-tests show no statistical difference between values of this property of MDF Type A and B (*p*-value is 0.091) and between MDF Type C and D (*p*-value is 0.492). Considerably more significant improvement in the property values is observed in the case of additional heat treatment and at the content of corn stalk fibres from 20% to 30%. The t-tests show a statistical difference between water absorption values of MDF Type E and F (*p*-value is $1.35.10^{-6}$) and MDF Type G and H (*p*-value is $1.55.10^{-7}$). Here, the water absorption decrease is by 1.73 times and 2.04 times. An explanation may be sought again in the destructive processes taking place, due to the higher amount of hemicellulose, by the additional heat treatment in the panels with higher content of corn stalk fibres. As a result of those processes, the hemicellulose disintegrates into simple sugars. And when this occurs, the conducting elements in the wood close [Altgen et al. 2016; Oliveira et al. 2017; Savov, V. et al. 2020 b]. The results obtained for the water absorption after the heat treatment of the eco-friendly panels with corn stalks and lignosulphonate was also reported in the manufacture of fibreboards with corn stalks and 13% kraft lignin [Thenk et al. 2017]. The additional heat treatment positively affects the waterproofness of fibreboards with lignosulphonate, obtaining values similar to those in the case of application of the kraft lignin.

The data for the thickness swelling of laboratory eco-friendly MDF panels are presented in Table 4.

**Table 4. Thickness swelling (24 h) of the laboratory eco-friendly MDF panels**

| MDF Type | Average (Mean) value, % | Standard deviation, % | Standard error, % | Probability, % | Confidence interval, % |
|---|---|---|---|---|---|
| Type A | 19.83 | 1.75 | 0.62 | 3.12 | 19.22÷20.44 |
| Type B | 16.22 | 2.07 | 0.73 | 4.52 | 15.50÷16.94 |
| Type C | 26.23 | 1.78 | 0.63 | 2.40 | 25.61÷26.85 |
| Type D | 20.11 | 2.75 | 0.97 | 4.84 | 19.16÷21.06 |
| Type E | 29.25 | 0.69 | 0.24 | 0.83 | 29.01÷29.49 |
| Type F | 8.51 | 1.19 | 0.42 | 4.93 | 8,10÷8.92 |
| Type G | 32.92 | 3.31 | 1.17 | 3.56 | 31.77÷34.07 |
| Type H | 7.70 | 0.69 | 0.24 | 3.15 | 7.46÷7.94 |

The thickness swelling of the manufactured panels varies from 7.7% to 32.92%, i.e. the increase is 4.28 times.

The change in the thickness swelling of the manufactured panels is presented in Fig. 2.

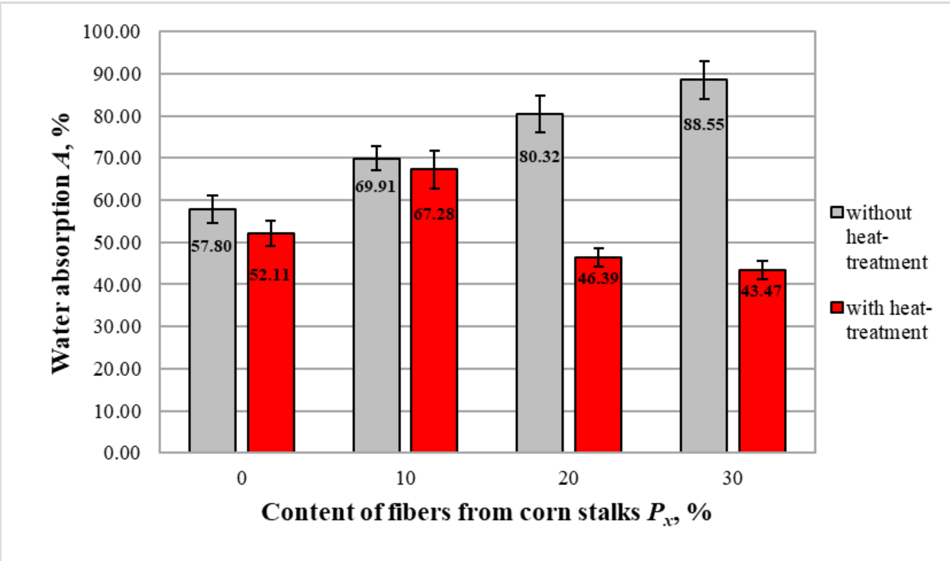


**Fig. 2. Water absorption of eco-friendly panels (error bars represent standard deviation)**

In the panels without additional heat treatment, the thickness swelling goes from 19.8% to 32.9%, which changes 1.66 times. As in the case of the water absorption, with the increase of the content of corn stalk fibres, deterioration of the values of the property also in the thickness swelling is observed. That is confirmed by t-tests, which showed that there is a statistical difference in the data on thickness swelling in MDF Type A and C (*p*-value is $4.24.10^{-6}$), MDF Type C and E (*p*-value is 0.0015), and MDF Type E and G (p-value is 0.0163). The decline of the property is as follows: with the addition of 10% corn stalk fibres – 1.32 times, in case of increase of the content from 10% to 20%, deterioration of 0.9 times is observed, and in case of growth of the content from 20% to 30% – of 1.1 times. The total decline with change in the content of corn stalk fibres from 0% to 30% is 1.66 times. Nevertheless, the panels with up to 20% corn stalk fibres content meet the MDF requirements even without the additional heat treatment. No type of the panels manufactured with lignosulphonate as a binder, without additional heat treatment, meets the requirements for MDF for use in a wet environment.

Despite the considerably prolonged duration of hot pressing of 90 s/mm, the additional heat treatment improves, lowering the thickness swelling values. Again, the performed t-tests showed a statistical difference in the data on thickness swelling in MDF Type A and B (*p*-value is 0.0022), MDF Type C and D (*p*-value is 0.0002), MDF Type E and F (*p*-value is $8.84.10^{-14}$), and MDF Type G and H (p-value is $5.10.10^{-8}$). The improvement of thickness swelling in the 0% and 10% content of corn stalk fibres is 1.22 times and 1.31 times. The panels manufactured without pulp from corn stalk participation meet the MDF requirements for use in wet conditions [EN 622-5].

The results obtained for the thickness swelling of the panels after additional heat treatment of the MDF with up to 10% corn stalks are similar to those reported in case of use of 10% UF resin and entirely corn stalk fibres [Kargarfard and Jahan-Latibardi 2011], as well as in case of use of 29% kraft lignin [Thenk et al. 2017]. That is, the considerable favourable effect of the additional heat treatment on the water resistance properties of MDF with lignosulphonate is confirmed again [Savov et al. 2020b].

In the panels with 20% and 30% content of corn stalk fibres, a considerable improvement in the property values is observed, with this being explained again with the processes of destruction of the lignocellulosic components of the board. The respective improvements in the property are by 3.43% and 4.28 times. These values are comparable with those obtained for panels entirely from corn stalks and 16% PF resin [Savov and Ivanova 2016].

The data for the modulus of elasticity of the laboratory MDF panels are presented in Table 5.

For the conditions of the experiment, the modulus of elasticity varies from 4467 to 3144 N/mm$^2$, or the total change in the values of the property is by 41.10%, Fig. 3.

In the panels without additional heat treatment, the modulus of elasticity in bending varies from 3853 N/mm$^2$ to 3180 N/mm$^2$, representing a relative change of 21.2%. With the addition of corn stalk fibres, deterioration in the property values is observed, which was also proved by other similar investigations [Lee et al. 2020].

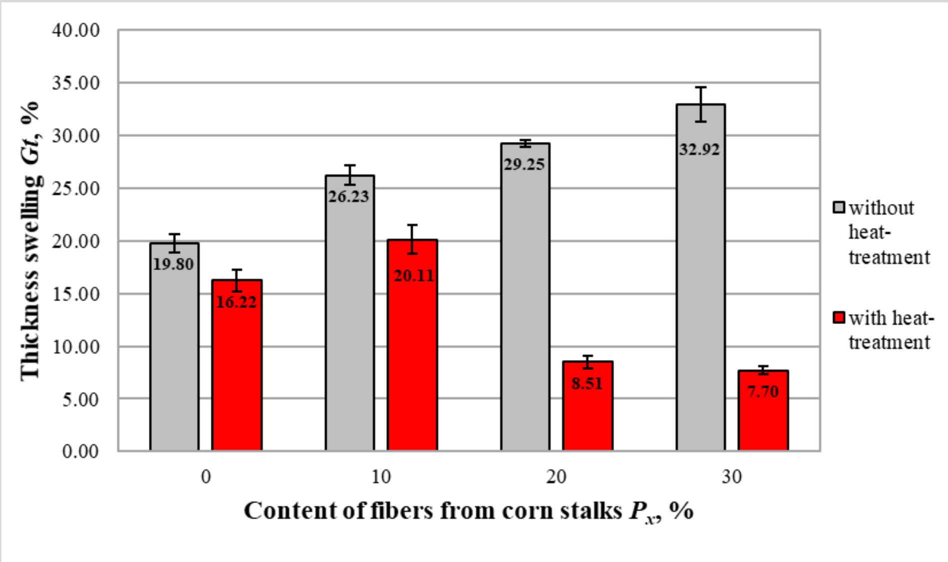


**Fig. 3. Thickness swelling of eco-friendly panels (error bars represent standard deviation)**

**Table 5. Modulus of elasticity (MOE) of the laboratory eco-friendly MDF panels**

| MDF Type | Average (Mean) value, N.mm$^{-2}$ | Standrd deviation, N.mm$^{-2}$ | Standard error, N.mm$^{-2}$ | Propability, % | Confidence interval, N.mm$^{-2}$ |
|---|---|---|---|---|---|
| Type A | 3853 | 531 | 188 | 4.88 | 3669÷4037 |
| Type B | 4467 | 489 | 173 | 3.87 | 4297÷4637 |
| Type C | 3704 | 455 | 161 | 4.34 | 3543÷3862 |
| Type D | 4349 | 267 | 94 | 2.17 | 4256÷4442 |
| Type E | 3424 | 351 | 124 | 3.63 | 3302÷3546 |
| Type F | 3311 | 405 | 143 | 4.33 | 3171÷3541 |
| Type G | 3180 | 423 | 150 | 4.71 | 3033÷3327 |
| Type H | 3144 | 436 | 154 | 4.90 | 2993÷3295 |

In case of an increase of the content of corn stalk fibres up to 10%, the deterioration is relatively lower, respectively, by 4%. With the rise of the content from 10% to 20%, the drop in the values of the modulus of elasticity is by 8.2%, and in case of increase of the content of corn stalk fibres from 20% to 30%, it is by 7.7%. However, the deterioration in the property values with the increasing content of corn fibre is relatively small. The t-tests show that statistical difference is observed only in the values of MDF panels without corn fibres (MDF Type A) and with 30% corn fibres (MDF Type G). The corresponding *p*-value is 0.0148. It should be emphasized that all manufactured panels, without additional heat treatment, meet the requirements to the modulus of elasticity for MDF for bearing structures and for use in wet conditions.

The additional heat treatment affects the modulus of elasticity of eco-friendly MDF panels. The performed t-tests show a statistical difference between the modulus of elasticity data at MDF Type A and B (*p*-value is 0.0306) and MDF Type B and C (*p*-value is 0.0051). With the application of additional heat treatment in the panels with 0% and 10% content of corn stalk fibres, an improvement in the modulus of elasticity values is observed. The respective improvements are by 15.9% and by 17.4%. The values of that property in the panels with up to 10% corn stalks are comparable with those in case of use entirely of corn stalk fibres and 13% kraft lignin, but at a considerably higher density of those panels – 1108 kg/m$^3$ [Teng et al. 2017]. The values obtained are also significantly better than those in the case of corn stalk fibres and use UF resin as a binder [Kargarfard and Jahan-Latibardi 2011; Lee et al. 2020]. Therefore, the favourable effect of the additional heat treatment on the modulus of elasticity of the panels with lignosulphonate is confirmed.

**Table 6. Bending strength (MOR) of the laboratory eco-friendly MDF panels**

| MDF Type | Average (Mean) value, N.mm$^{-2}$ | Standard deviation, N.mm$^{-2}$ | Standard error, N.mm$^{-2}$ | Probability, % | Confidence interval, N.mm$^{-2}$ |
|---|---|---|---|---|---|
| Type A | 30.54 | 2.87 | 1.01 | 3.32 | 29.55÷31.53 |
| Type B | 43.12 | 5.17 | 1.83 | 4.24 | 41.33÷44.91 |
| Type C | 25.92 | 2.45 | 0.87 | 3.34 | 25.07÷26.77 |
| Type D | 32.57 | 2.69 | 0.95 | 2.92 | 31.64÷33.50 |
| Type E | 26.02 | 3.53 | 1.25 | 4.8 | 24.80÷27.24 |
| Type F | 23.66 | 3.13 | 1.11 | 4.68 | 22.58÷24.74 |
| Type G | 19.9 | 1.62 | 0.57 | 2.89 | 19.34÷20.46 |
| Type H | 19.14 | 2.58 | 0.91 | 4.76 | 18.25÷20.03 |

Due to the destructive processes that have taken place in case of the additional heat treatment in the panels with 20% and 30% content of corn stalk fibres, deterioration, respectively decrease, in the values of the modulus of elasticity in bending property is observed. That is confirmed by t-tests in which it was found that there is a statistical difference in the values of the modulus of elasticity in MDF Type D (10% corn fibres with additional heat treatment) and MDF Type F (20% corn fibres with additional heat treatment). The corresponding *p*-value is $5.53.10^{-5}$.

The data for the bending strength (MOR) of the laboratory eco-friendly MDF panels are presented in Table 6.

The bending strength of the manufactured panels varies from 19.14 to 43.12 N/mm$^2$, or the total change in the property values is 225%, Fig. 4.

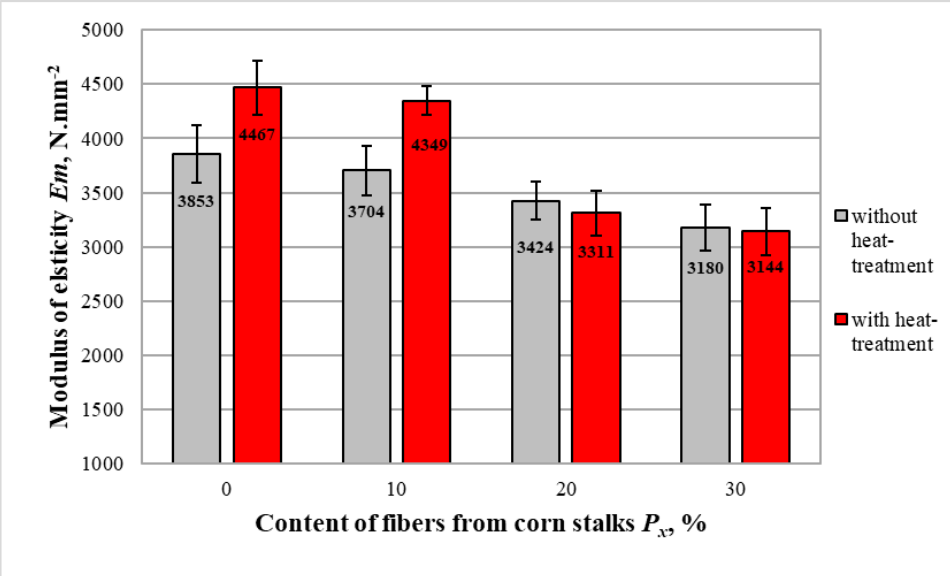


**Fig. 4. Modulus of elasticity of eco-friendly panels (error bars represent standard deviation)**

In the panels without additional heat treatment, the bending strength varies from 30.54 to 19.9 N/mm$^2$, representing a total change of 54%. Deterioration by 18% is observed in the case of the addition of only 10% corn stalk fibres. That is confirmed by the conducted t-test, which found a statistical difference between MDF Type A and C (*p*-value is 0.0042). In practice, under the conditions of the experiment, no difference in the bending strength of the panels at 10% and 20% content of corn stalk fibres is recorded, which is also confirmed by the conducted t-test (*p*-value is 0.9479). In case of an increase of the content of corn stalk fibres from 20% to 30%, a considerable, by 30.8%, deterioration of the values of the bending strength property is observed. The *t*-test also confirms a statistical difference in bending strength data between MDF Type E and G (*p*-value is 0.0012).

Nevertheless, even without applying additional heat treatment, the panels manufactured with lignosulphonate as a binder with up to 20% participation of corn stalk fibres meet the requirements to the bending strength property for general-purpose MDF for use in dry conditions. The panels with up to 10% content of corn stalk fibres meet the requirements for general-purpose MDF for use in wet conditions. The board manufactured entirely from wood-fibre mass meets the requirements for MDF for bearing structures and for use in dry conditions [EN 622-5].

The additional heat treatment affects the bending strength of eco-friendly MDF with the participation of fibres from corn stalks and bonded with lignosulfonate. The performed t-tests show a statistical difference between the bending strength values for MDF Type A and B (*p*-value is $8.77.10^{-5}$) and MDF Type C and D (*p*-value is 0.0001).

In the MDF panels with 0% and 10% content of corn stalk fibres, the additional heat treatment exercises a positive influence on the bending strength. The respective improvement is by 43.2% at the board without corn stalk fibres and by 25.7% at 10% content of corn stalk fibres. As a result of the additional heat treatment, the MDF panels manufactured entirely from wood-fibre mass meet MDF requirements for bearing structures and for use in wet conditions.

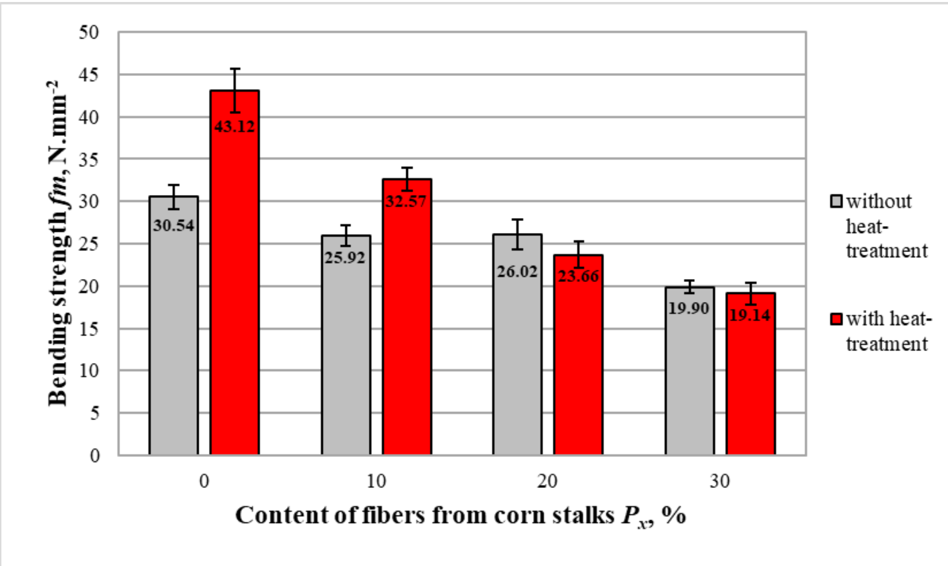


**Fig. 5. Bending strength of eco-friendly panels (error bars represent standard deviation)**

The board with 10% corn stalk fibres meets the requirements to the bending strength property for MDF panels for load-bearing structures and use in dry conditions. The values obtained for the bending strength of the panels without additional heat treatment are similar to those in panels with corn stalk fibres and UF resin [Kargarfardand and Jahan-Latibardi 2011; Lee et al. 2020].

After the additional heat treatment of the MDF with up to 10% cornstalk fibres, the bending strength is similar to that reported in the use of 9% kraft lignin but at a considerably higher density [Theng et al. 2017].

In the panels with the content of corn stalk fibres of 20% and 30% with application of the selected regime for additional heat treatment, deterioration of the bending strength property is observed. It confirms that the additional heat treatment shall be conformed to the ratios of the wood to the non-wood lignocellulosic raw material or, in other words, shall be conformed to the chemical composition of the raw materials.

## Conclusions

As a result of the investigation performed, it has been found that eco-friendly (from lignocellulosic residual agricultural products – corn stalks, and binders without emissions of formaldehyde – lignosulphonate) thin MDF panels may be successfully manufactured. The corn stalks represent an alternative to the scarce wood raw material for fibreboards manufacture. Nevertheless, as a result of the investigation performed, it has been found that it is not appropriate that the content of corn stalk fibres exceeds 20% in the case of the use of lignosulphonate as a binder.

The main novelty of the research is the study of the effect of additional heat treatment on the properties of MDF panels with the participation of fibres from corn stalks bonded with lignosulfonate. As a result of the study, recommended values for the content of corn fibres in the composition of eco-friendly MDF panels with lignosulphonate adhesives were derived. The additional heat treatment improves to a considerable extent the hydrophobic and mechanical properties of the panels manufactured with calcium lignosulphonate. In the applied mode of additional heat treatment in the MDF panels with 20% and 30% content of corn stalk fibres, destructive processes in the components of the panels are observed, which leads to loss of mass, respectively decrease in the density of the panels. The destructive processes that have taken place in the MDF panels with 20% and 30% content of corn stalk fibres and subjected to additional heat treatment lead to a considerable decrease (improvement) in the water absorption and the thickness swelling of the panels, but also the deterioration of their mechanical properties. That leads to the conclusion that softer regimes for additional heat treatment shall be used at the content of corn stalk fibres above 20%.

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